Experimental Determination of Temperature during Rotary Friction Welding of Dissimilar Materials

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Abstract

The purpose of this paper is describes a method of temperature monitoring in bonding interface during the rotary friction welding of dissimilar materials. As it is directly related to the mechanical strenght of the junction, its experimental determination in real time is of fundamental importance for understanding and characterizing the main process steps, and the definition and optimization of parameters. The temperature gradients were obtained using a system called Thermocouple Data-Logger, which allowed monitoring and recording data in real-time operation. In the graph temperature versus time obtained were analyzed the heating rates, cooling, determined the maximum temperature occurred during welding, and characterized every phases of the process. The system efficiency demonstrated by experimental tests and the knowledge of the temperature at the bonding interface open new lines of research to understand the process of friction welding.

Keywords

Friction Welding; Aluminum; Stainless Steel; Dissimilar Materials; Temperature

Introduction

The rotary friction welding (RFW) is a special process that occurs in the solid state. It provides high productivity, excellent repeatability, low cost, and finds its greatest application in the production of dissimilar materials joints used in aerospace, nuclear, marine and automotive fields. All process happens at temperatures lower than the melting point of the materials involved and the joints produced are of excellent quality featuring superior mechanical properties of the metals that were joined.

In the RFW, one part is fixed and rotated by a motor unit to a predetermined speed, and the other is positioned, aligned and moved by a hydraulic piston to touch the part that is spinning. After that, P1 pressure is applied for a given time (t1), the machine brakes until it reaches zero speed, and P2 pressure is applied during a t2 time, finishing the welding [2].

Parameters of welding (rotation per minute (RPM), P1 and P2 pressures, t1 and t2 times) are defined by welding procedures established for each material or materials and according to the type of the equipment employed. Figure 1 shows the phases of process.

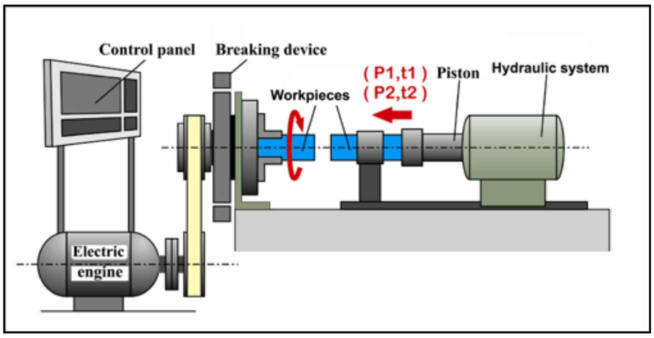


FIGURE 1 PHASES OF CONVENTIONAL FRICTION WELDING PROCESS. (A) PERIOD OF APPROXIMATION; (B) P1, T1, APPLICATION; (C) END OF P1, T1, AND BREAKING OF THE MACHINE (RPM=0); (D) P2, T2 APPLICATION AND FINISH WELDING [2].

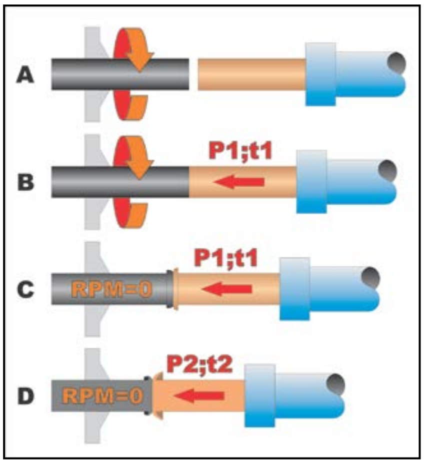


FIGURE 2 – EQUIPMENT OF ROTARY FRICTION WELDING [2]

Figure 2 shows the basic layout of RFW equipment, whose flawless performance and timing are of fundamental importance in the quality of joints obtained by this process.

When using this process to the union of two materials, it is very important to know the temperature in the bonding interface, because it directly interferes with the formation of the crystal structure of the Heat Affected Zone (HAZ), influencing the mechanical and metallurgical properties of welded joint [2].

All the heat necessary for welding is produced by the direct conversion of mechanical energy into thermal energy. It is a complex metallurgical process which involves a series of variables such as pressure, time, travel speed, rotational speed, accompanied by physical phenomena: heat generation by friction, atomic diffusion, plastic deformation and formation of intermetallic compounds. During the relative motion of surfaces, a significant amount of heat is dissipated causing temperature increase, even with small values of loads and sliding speeds [1].

In friction welding the heat generation occurs differently from conventional welding processes for fusion; however there is a similarity in the temperature distribution on the joint of union of base metals [2]. The amount of heat generated at the bonding interface or heat input in RFW is a consequence of the friction and work of plastic deformation due to relative motion between both materials.

The temperature at the surface depends on the applied pressure, rotational speed, thermal conductivity, and also on the coefficient of friction. Heat dissipation is an automatic process since friction and adhesion occur in places where micro welds cause an increase in the rate of heat dissipation, which contributes to an increase in micro welds and bonding of two surfaces [1].

There are many published studies on RFW and on its thermal effects through experimental and analytical methods, which were conducted by researchers in different countries according to their importance in understanding the mechanisms that involve the process.

Vill, V. I. [8], Ylbas, *et al* [9], Sahin, Mumin [10], Chalmers, R.E. [11], Zepeda, C. M. [12], Nikolaev, *et al* [13], Aritoshi, *et al* [14], Ambroziak, *et al* [15], Isshiki, Y. *et al* [16], Kusçu, *et al* [17], Sluzalec, Andrzej [18], Lee. B. W., *et al* [19], Kimura, Masaaki, *et al* [20], Ochi, H., *et al* [21], Banker, John, *et al* [22], conducted several studies involving the joining of dissimilar materials and wrote articles on the mechanical properties, metallurgical and thermal effects of the welded parts RFW.

In this study, a method called Thermocouple Data-Logger (TDL) for monitoring the temperature in the bonding interface in real-time operation of dissimilar materials AA1050 aluminum with AISI 304 stainless steel, was used [2]. Through this system, is it possible to monitor, determine the beginning and the end of each stage of welding, to analyze the different heating rates and, cooling, and characterize all stages of the process through time *versus* temperature curves in real-time. This method can also be used to monitor the temperature during friction welding of other combinations of materials like stainless steel to cooper, mild steel to aluminum, where only one is subjected to plastic deformation and the other not, allowing the attachment of the thermocouple.

Interaction among the Parameters

Although each welding parameter has its importance individually, the interaction among them and their subsequent stages is that results in the formation of a junction with good quality and optimal mechanical properties for your application.

Generally speaking, a friction welding operation can be divided into two phases: the phase of heating and forging stage. In the heating phase, the interaction between the parameters (P1 pressure, t1 time, travel speed, RPM) aims at removing the layer of oxides and impurities of the interfaces of materials that will be joined and do that the friction between them elevate the temperature up to a certain value for that, with the application of the P2 pressure in the time interval t2, the union between the materials will be undertaken and completed successfully.

Chosen appropriate welding parameters, friction welding can join two dissimilar materials in a full-strength weld, without sacrificing weld integrity or strength. The friction welding process creates a weld interface that consists of an entirely new material composed of the two original materials [23].

Temperature at Bonding Interface

At bonding interface, due to the velocity gradient across the welding interface (maximum at the circumference and minimum at the centre in rotary friction welding) and due to other parameters, such as the friction pressure, heat generation is not uniform [23].

According to the uneven temperature distribution, the HAZ becomes thicker from the centre to the periphery. It has been reported that the interface temperature at the centre of a solid bar does not reach the maximum interface temperature, or even that of the measured average [23].

The heat generation is least at the center of the weld and it increases radially as distance from the center of the weld increases, as illustrated in Figure 3. This variation of heat generation is due to difference in relative speed. The speed at the bonding interface increase radially of the center of the weld to the periphery [24].

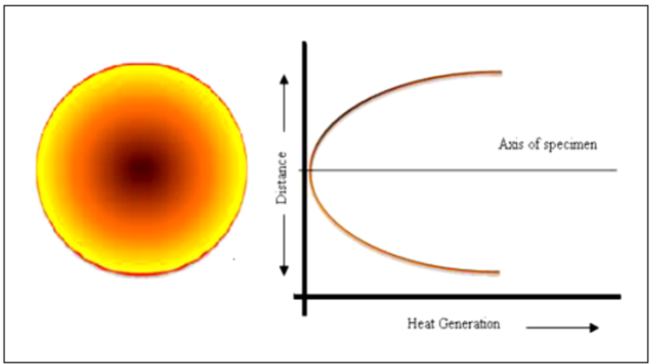


FIGURE 3 ILLUSTRATION OF HEAT GENERATION (INCREASES RADIALLY AS DISTANCE FROM CENTRE INCREASES) [24].

When two dissimilar materials are joined, such as AA1050 aluminum and AISI 304 stainless steel, with different properties by this process, the heat generated by friction between the two materials is spread differently in each material. The thermal conductivity of aluminum is three times higher than in stainless steel, influencing directly the rate of heating and cooling that occur during the process. The surface roughness of the interfaces that will be attached can also change the heating rates in the initial stages of the welding operation and influence the diffusion mechanism, which occurs mainly in the first phase of welding (heating phase) [25].

The temperature gradient and thermoplastic deformations determine microstructural changes, diffusion phenomena, and mechanical properties of the final product [3]. During the welding of aluminum with stainless steel, the rise of temperature in the bonding interface causes a large plastic deformation and flash formation in AA1050 aluminum. Part of the heat is dissipated into the flash and into the contacts of the materials with the components of the welding equipment.

As can be seen in Fig. 4, during the welding of AA1050 aluminum with stainless steel AISI 304, the initial temperature is higher in the peripheral region due to the higher tangential velocity, and then it extends to the centre of interface increasing with the heating time (t1, t2, t3, t4, t5, t6, t7, t8, t9). After a given time, the difference between the temperatures is going to be very small, especially on the aluminum side that has a high thermal diffusivity [6]. When the material reaches the critical temperature Tc, the material begins to undergo severe plastic deformation leading to formation of the flash, which is also responsible for part of the dissipation of heat generated by the process.

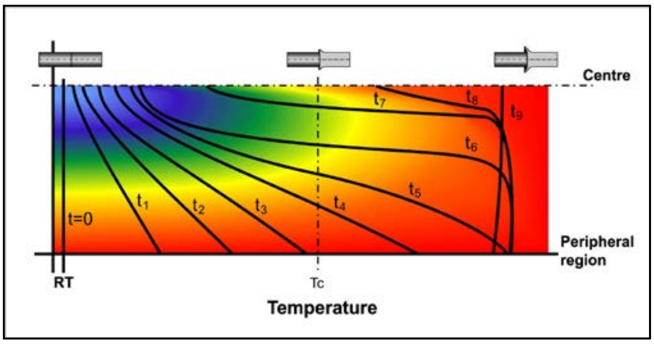


FIGURE 4 DISTRIBUTION OF TEMPERATURE ON THE BONDING INTERFACE: RT: ROOM TEMPERATURE; TC: CRITICAL TEMPERATURE. SOURCE: ADAPTED FROM [4].

Experimental Procedure

Materials and surfaces preparation

The materials used in this study were: AA1050 aluminum (commercially pure aluminum, 99.5%) and AISI 304 austenitic stainless steel. Both materials were machined with a diameter of 14.8 mm and lengths of 100 and 110 mm, respectively. After machining, they were subjected to be cleaned with acetone in order to remove organic contaminants, such as oils, greases, and so on. Tables 1 and 2 present chemical compositions and mechanical properties of the materials [26].

TABLE 1 NOMINAL CHEMICAL COMPOSITIONS OF MATERIALS

AA 1050 Aluminum	Elements (wt%)							
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
	0.07	0.26	<0.001	-	<0.001	-	<0.002	<0.0
AISI 304 stainless steel	Si	S	P	Mn	C	Cr	Ni	-
	0.38	0.024	0.036	1.67	0.054	18.2	8.0	-

TABLE 2 MECHANICAL PROPERTIES OF MATERIALS USED IN THE PRESENT STUDY

Material	Mechanical properties				
	Strenght σ		Elongation ε (%)		Modulus of elasticity E (GPa)
	Yield	Maximum	Maximum	Fracture	
AA 1050 aluminum	44.70	78.48	21	43	59.12
AISI 304 stainless steel	354.69	643.79	48	63	177.10

Friction Welding Equipment

A rotary friction welding machine, GATWIK brand, was used with fixed rotational speed of 3,200 RPM, P1=2.1 MPa, t1=32 seconds, P2=1.4 MPa and t2=2 seconds. These parameters refer to welding procedures by friction between the related materials described in a previous paper [2], optimized and qualified with the fracture occurring in the AA1050 aluminum, away from the bonding interface with the mechanical resistance superior of AA1050 aluminum [6]. Temperature in the bonding interface was also monitored with the heating time t1 extended to 52 seconds for analysis and comparison of the curves and rates of warming and cooling during welding. The materials were placed as shown in Fig. 5.

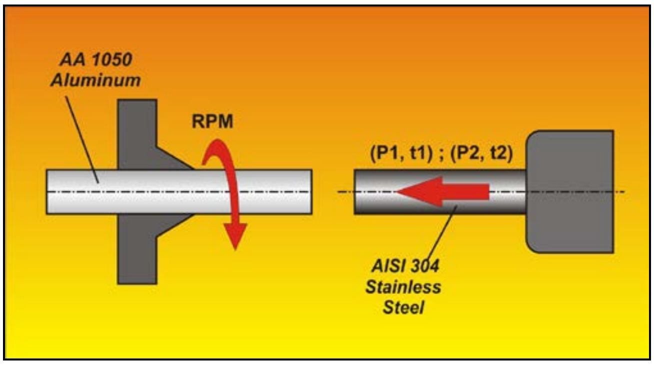


FIGURE 5 SCHEMATIC VIEWS OF THE MATERIALS PLACED BEFORE WELDING

Temperature Monitoring During Friction Welding Process

Temperature is the most important parameter of a joint in the solid state by controlling the kinetics of thermally activated processes involved in diffused junctions. In the joints that occur at high temperatures, the atomic mobility increases and helps the movement displacement of atoms through the bonding interface [5].

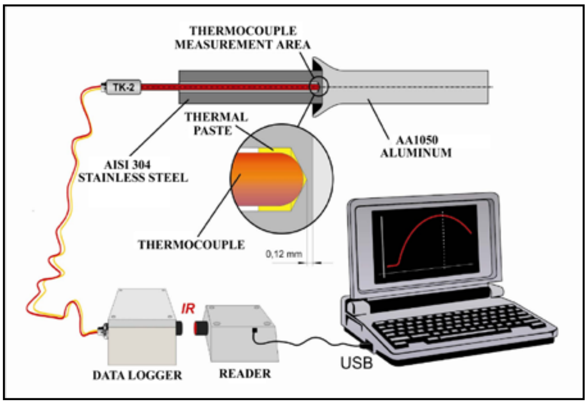
As the temperature in the interface is directly related to the characteristics of the HAZ and with the strength of joints obtained by the RFW, its monitoring on a trial is extremely important for understanding the characteristics of this process.

For data acquisition, the TDL system was used, coupled to a notebook that provided real-time graph of the temperature during the process. We used a thermocouple type K (cromel-Alumel) measured and calibrated, ECIL brand, positioned on the pin of AISI 304 stainless steel, axial region, at a distance of 0.12 mm of the interface (Fig. 6) and a data logger, brand NOVUS, with 16 k of storage capacity, which allowed the collection of data in 0.5 second intervals during all the process. It was also used thermal paste of brand IMPLASTEC to improve the area of contact between the thermocouple tip and the surface of stainless steel pin. A total of five measurements was realized during the welding operation.

The TDL system was settled up by software in a Windows environment and it provides resources for collecting, plotting, analyzing, and exporting logs. Communication between the data logger and the notebook is realized in a few seconds via infrared optical non-contact [2].

Figure 5 shows an illustration of the TDL system used for temperature monitoring in real-time [2].

FIGURE 6 TDL SYSTEM COMPOSED OF K-TYPE



THERMOCOUPLE, DATA LOGGER, INFRARED (IR) READER IR, AND NOTEBOOK TO MONITOR THE TEMPERATURE

Results

In welding tests, which were performed with temperature monitoring by the TDL system, the pins of AISI 304 stainless steel showed changes in the color of the surface near the bonding interface due to

displacement of heat flow. Pins made from the AA1050 aluminum also show displacement of heat flows, but they are not visible on the surface due to the characteristics of the material. Fig. 7 shows the welded pins and the flashes formed.

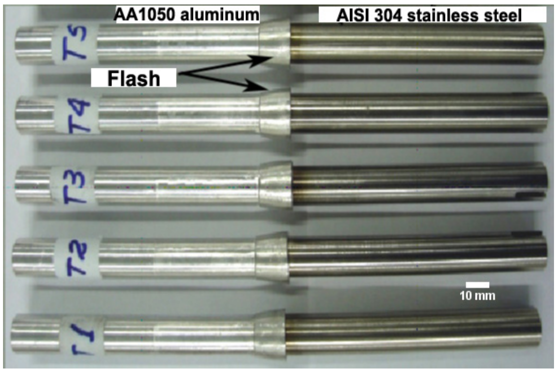


FIGURE 7 ELDED PINS BY RFW WITH THE SAME PARAMETERS

The thermocouple fixed in the axial region of the cylindrical pin of AISI 304 stainless steel (Fig. 6) recorded a maximum temperature of 376 °C during the welding process in real-time of 34 seconds (Approach + t1 + t2), shown in Fig. 8 [2].

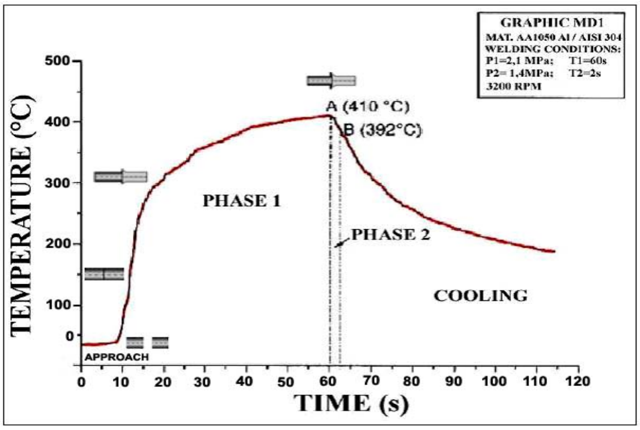


FIGURE 8 GRAPH TEMPERATURE VERSUS TIME – AA 1050 ALUMINUM AND AISI 304 STAINLESS STEEL WITH TOTAL TIME OF 34 SECONDS

In the graph obtained, all phases of pressure (P1=2.1 MPa) at the time of 22 seconds, the second phase of forging with application of pressure of the welding process, the approach with a time of ten seconds, the first phase of heating with application (P2=1.4 MPa) at the time of two seconds, and the completion of welding were characterized. It was observed that when the rotational speed was stopped at the end of the first phase (point A – 376 °C), a drop in temperature during the forging phase (B – 350 °C) occurs, finishing the welding. Hence, the phase of cooling to room temperature starts.

This type of cooling does not interfere in the characteristics of the HAZ and the mechanical properties of the junction between the materials involved, mainly because the AA 1050 aluminum is not heat-treatable and has high purity (minimum 99.50% Al), which was proven by the results of the analysis and testing in this study. However, in the case of welding AISI 304 stainless steel with heat-treatable alloys (series 2XXX, 6XXX and 7XXX), the slow cooling can change the characteristics of the HAZ, as the proximity of the temperature values obtained in the bonding interface with the values used for heat treatment of solubilization and aging of these alloys [2].

With time t1 extended to 52 seconds, the process temperature with total time of 62 seconds (approach=eight seconds; t1=52 seconds; t2=2 seconds), using the same welding parameters of P1 and P2, there is an increase of temperature during the heating phase, and over time it was stabilized to the temperature of 410 °C, point "A". After applying the pressure P2 and the time t2, the welding was completed with a temperature of 392°C, point "B". The air cooling performed at room temperature (30°C) showed similar cooling rates to the previous example (total time of 34 seconds). Figure 9 [2] shows all process phases and temperatures monitored during welding of AA1050 aluminum with AISI 304 stainless steel.

Another important result of the analysis performed is that the maximum temperature monitored is within the range of the hot forging temperature of the alloy AA 1050, between 315 to 430 °C [7]. This knowledge allows the default parameters of RFW for a given diameter using data supplied by the graph, which allows to eliminate a series of preliminary stages in obtaining parameters for the welding of dissimilar materials.

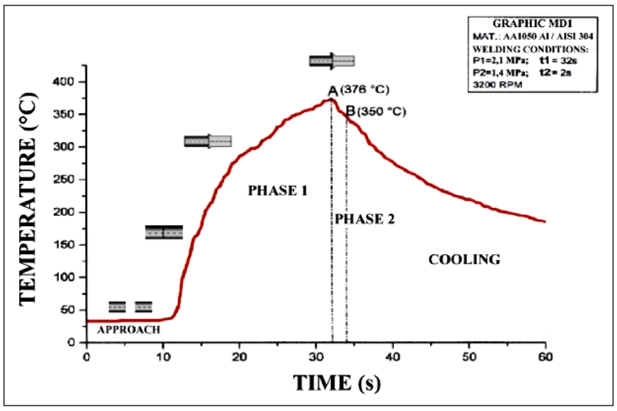


FIGURE 9 GRAPH TEMPERATURE *VERSUS* TIME – AA 1050 ALUMINUM AND AISI 304 STAINLESS STEEL WITH TOTAL TIME OF 62 SECONDS

In the phase 1 (heating), the relationship among the parameters (P1 pressure, t1 time, travel speed and rotational speed) aims at increasing the temperature at the bonding interface through the friction between the contact surfaces. This rapid increase in temperature with the constant application of pressure promotes a severe plastic deformation and removal of oxides and impurities through the flash, providing ideal conditions for the occurrence of the phenomenon of diffusion. In the phase 2 (forging), the temperature at the interface should have reached a certain level so that with the application of P2 pressure in the time interval t2, the union between the materials was successfully completed. If this relationship does not occurs satisfactorily in the heating phase, and between it and the forging phase the cycle of welding ends, the layers of oxides and impurities cannot be removed completely from the surfaces. The temperatures necessary for the occurrence of diffusion and forging may not be enough for the perfect union of the materials involved, resulting in a junction with poor mechanical properties. Figure 10 shows the flash formed by plastic deformation and the bonding interface (t1 extended to 52 seconds) after the machining [26].

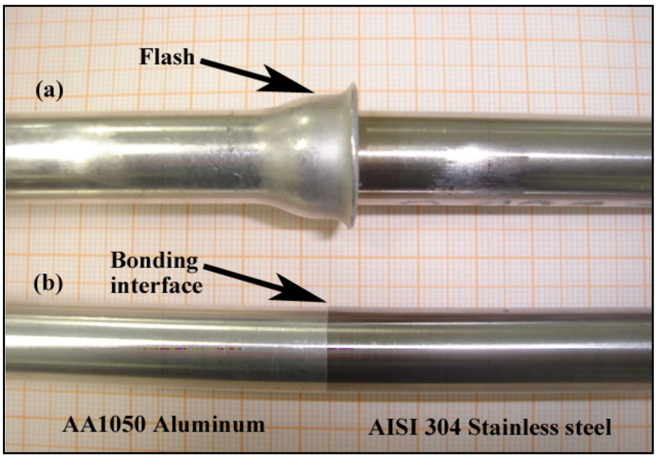


FIGURE 10 (A) SHAPE OF THE FLASH IN RFW; (B) BONDING INTERFACE AFTER MACHINING (SAMPLES ON GRAPH PAPER).

Conclusions

The temperature monitoring during welding tests as used parameters recorded the maximum temperature of 374 °C. This result confirmed that the temperature at the bonding interface during welding coincides with the range of hot forging of AA1050 aluminum (315-430 °C), as quoted in the literature [7].

The highest rates of heating occurring in the first ten seconds of the first phase of welding (heating phase) tend to stabilize as a function of deformation and plastic flow of the AA 1050 aluminum.

Knowing the temperature curves for certain joints between dissimilar materials, It can be used to obtain optimization and qualification of parameters, reducing stop times for equipment set up in different tests that involve RFW, machining, and mechanical testing.

The results of this study were of fundamental importance for understanding and comprehending the RFW, allowing the characterization of the different phases that involve this process and observation of heating and cooling rates. This knowledge will allow the opening of new lines of research, optimization, cost reduction, and increased productivity.

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